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13. ABSTRACT (Maximum 200 words)

Structure of the crust and upper mantle in southern and central Africa is investigated using seismic data from the Global Seismic Network and a special PASSCAL deployment of stations in Tanzania, East Africa. Structure models are developed to understand wave propagation important to issues concerning the verification of the Comprehensive Test Ban Treaty and to also investigate the tectonic basis for the African "Superswell", a previously identified region of anomalously high topography covering the southern half of the African continent. Through modeling of regional and teleseismic P, S, and Pnl phases it is found that the upper mantle has relatively high velocities down to depths exceeding 700 km. Well defined upper mantle triplications recorded by the Tanzania array show that the 410 km and 670km discontinuities are better characterized by broad gradient zones and Pnl waveforms suggest that no upper mantle low velocity zone exist within the

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Executive Summary

Introduction

The recent signing of the Comprehensive Test Ban Treaty (CTBT) underscores the need for detailed knowledge of seismic source characterization and wave propagation over the entire globe. Verification of compliance with the CTBT will require international seismic monitoring of many regions which are not particularly well explored nor understood. This is particularly true for the African continent which, until recently, has not been well-instrumented for seismic studies.

The goals of our research program have been to study natural and man-made seismic sources within southern Africa to understand the velocity structure of the earth there. The techniques that were used to accomplish this were based around the use of synthetic seismograms to model observed broadband data recorded by existing Global Seismic Network (GSN) stations and from a special PASSCAL experiment fielded in the country of Tanzania, East Africa. Figure 1 shows the area of study in this research with the locations of seismic stations, seismic sources used, and large-scale geologic terranes. The structure of southern Africa is composed of Archean cratons (Kalahari and Tanzania) separated by Proterozoic "mobile belts" which were presumably sites of continent-continent collision. Extensional tectonism during the Permian-Jurassic and Cenozoic produced extensive rift basins with recent tectonism providing for many of the seismic sources used in this project.

Although the grand view of African structure is complex, generally there are only small differences in structure between Proterozoic and Archean crystalline terranes. This produces a wave propagation regime repleat with
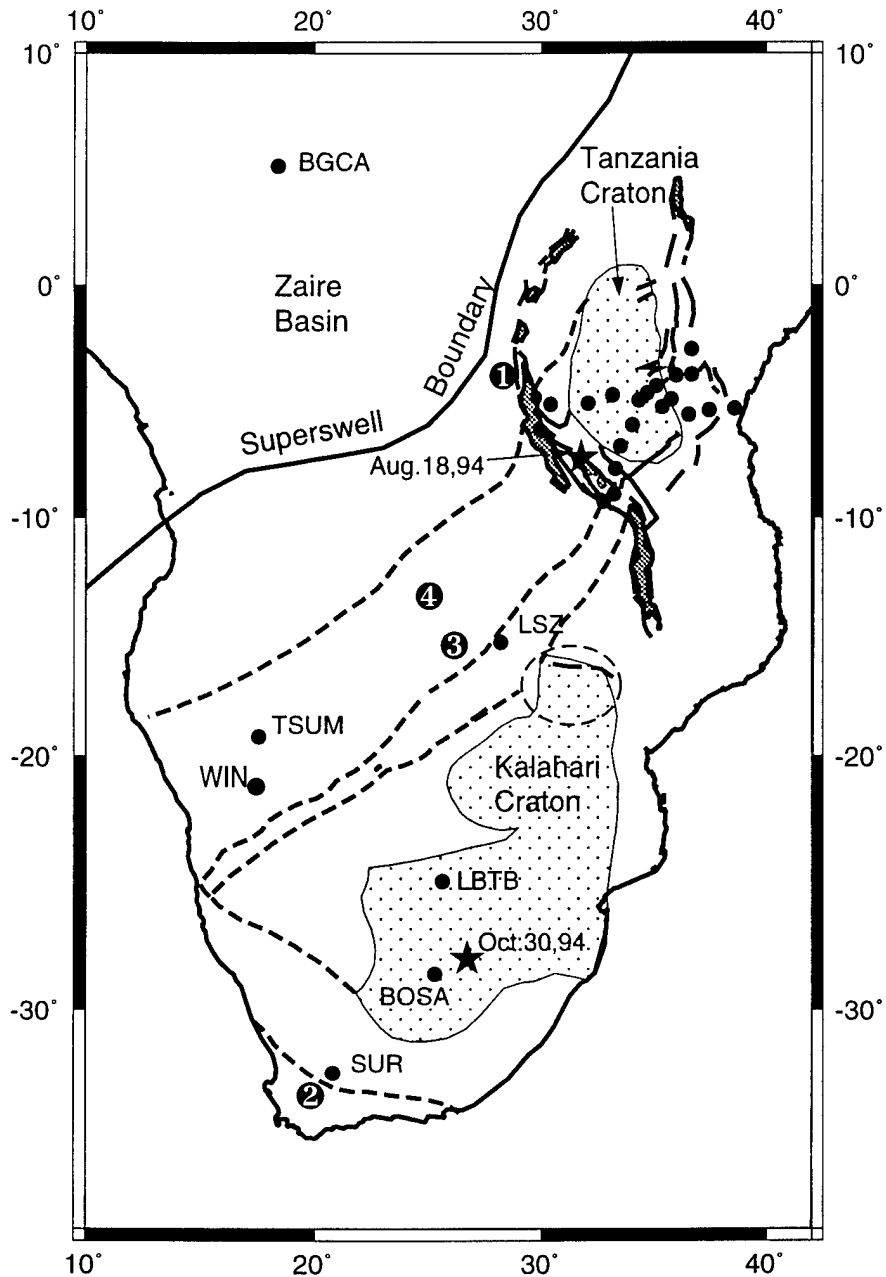
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Figure 1: Index map of southern Africa. The Kalahari and Tanzania cratons are shown in stippled pattern. Solid circles across the Tanzania craton show location of stations of the Tanzania network. Other solid circles show the location of GSN and WWSSN stations. The numbered solid circles show the location of events used in the Pnl study while the stars show the location of events used in the upper mantle study. The dashed ellipse at the northern end of the Kalahari craton shows the location of bottoming points for upper mantle P waves recorded by the Tanzania network from the 10/30/94 mine tremor. Heavy dashed lines show the boundaries of the major Proterozoic mobile belts and the solid heavy line the continental boundary of the African Superswell.

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distinct and clear seismic phases seen on seismogram data. We have modeled several kinds of broadband seismic data to determine the nature of velocity gradients within the mantle of Proterozoic terranes, the structure of the upper mantle beneath the northern end of the Kalahari craton, and to study source parameters of induced mine tremors in South Africa. The view that emerges from these studies is that much of the wave propagation in the crust and mantle can be explained using fairly simple vertically-inhomogeneous earth models. Synthetic seismograms computed for appropriate point sources show excellent correpondence to the data suggesting that these models can be used to predict waveforms from other events of interest in order to determine source parameters. Hence, we believe some progress has been made in the regionalization of the structure of southern Africa which should find use in CTBT monitoring.

In addition to these results in seismic wave propagation, we have also approached this work with the goal of determining the tectonic mechanisms that give rise to the African Superswell [*Nyblade and Robinson*, 1994]. The African Superswell is an area of anomalously high topography encompassing southern Africa and much of the southern Atlantic basin. The continental boundary of the Superswell across Africa is shown on Figure 1. The plateaus of East and Southern Africa are about 500 m higher, on the average, than expected compared to topography in other preCambrian terranes. Some of the source for this topographic anomaly has been suggested to lie in the upper mantle. Presumably, the uplift is caused by lower than average mantle densities, possibly influenced by thermal perturbations from upwelling asthenosphere. The results of our work on the upper mantle show that there is little evidence for such thermal perturbations and that the mantle is relatively fast, compared to the world-wide average, down to 700 km. Thus,

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we have come to the preliminary conclusion that the compensation for the high topography must be occurring deeper in the mantle.

Finally, we have discovered that as more GSN seismic stations come on line with time, the number of problems to investigate in this interesting area continues to grow. Our research has naturally progressed to comparative structure studies with other African regions such as the Afar in Ethiopia. There is no doubt that greater data availability will make it possible to perform higher resolution studies of sources and structure within Africa to illuminate the geophysical issues important to the CTBT as well as major scientific problems of global tectonics.

P Wave Velocity Structure of Proterozoic Upper Mantle Beneath Central and Southern Africa

Published in *Nyblade et al.* (1996b), this work represented our early effort in characterizing the structure of the uppermost mantle, or "lid", within the Proterozoic mobile belts to the north and east of the Kalahari craton (Figure 1). *Clouser and Langston* (1990) investigated the upper mantle of the Kalahari craton using Pnl waveforms from moderate events recorded at regional distances. They found that the upper mantle had high velocities and a positive velocity gradient with depth. Pnl waveforms are particularly good for this kind of study since they are composed of Pn waves, which travel in the uppermost mantle, and P-coupled Pl waves which are trapped in the crustal waveguide. Several studies have shown that the Pl wave is a relatively stable, high amplitude phase which is affected by average properties of the crust. Once average crustal velocities and thickness are known, the

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amplitude and timing of Pn relative to Pl can be used to infer mantle P wave velocity and information on the nature of velocity gradients.

Clouser and Langston (1990) found that Pn waves propagating along shield paths had amplitude and frequency characteristics consistent with turning waves in the mantle lid, implying a positive velocity gradient with depth. *Nyblade et al.* (1996b) modeled several events at WIN station and one event at BCAO to find that Proterozoic terranes could be best characterized by constant velocity in the uppermost mantle. Figure 2 is an example of the waveform fits that can be attained for an event recorded at WIN.

BCAO station lies outside of the Superswell and we modeled an event at somewhat larger distances than those events recorded at WIN. We found that the data required modeling of deeper structure at depths of 400km. The resulting models which fit the waveforms (Figure 3) are shown in Figure 4. They suggest that the upper mantle does not have much gradient down to 300 km or so and that the 400 discontinuity may not be very distinct. Although there are resolution problems with using data at a single distance, this result fore-shadows the result of detailed upper mantle modeling using P waves recorded by the Tanzania network.

The results of this particular study showed that there are some differences in upper mantle structure between Proterozoic and Archean terranes within southern Africa, primarily in the nature of the velocity gradient. However, mantle P-wave velocities are seen to be normal or high beneath both areas implying that there is little expression of possible lithospheric thinning by upwelling asthenosphere. This suggests that the compensation mechanism for the uplift of the southern and eastern plateaus of Africa must be occurring at larger depths.

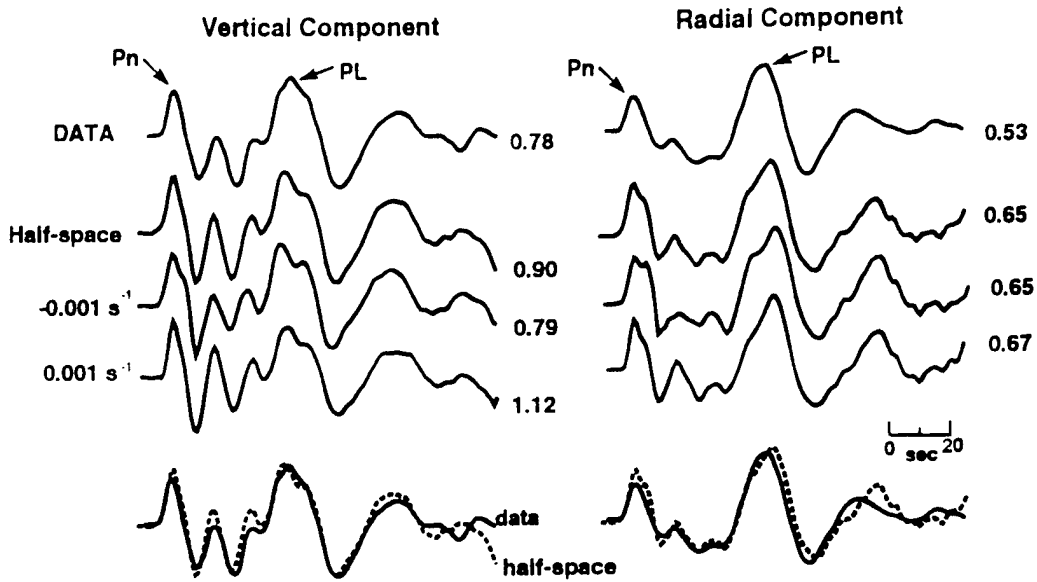## Event 2 WIN

Vertical Component

Radial Component

Figure 2: Data and synthetic seismograms for Event 2 (Figure1) recorded at WIN station. The synthetics are for a halfspace mantle and mantles with P-wave velocity gradients of -0.001 /s and +0.001/s. The numbers to the right of each waveform gives the Pn/Pl amplitude ratio. A halfspace mantle works well in explaining these waveforms.

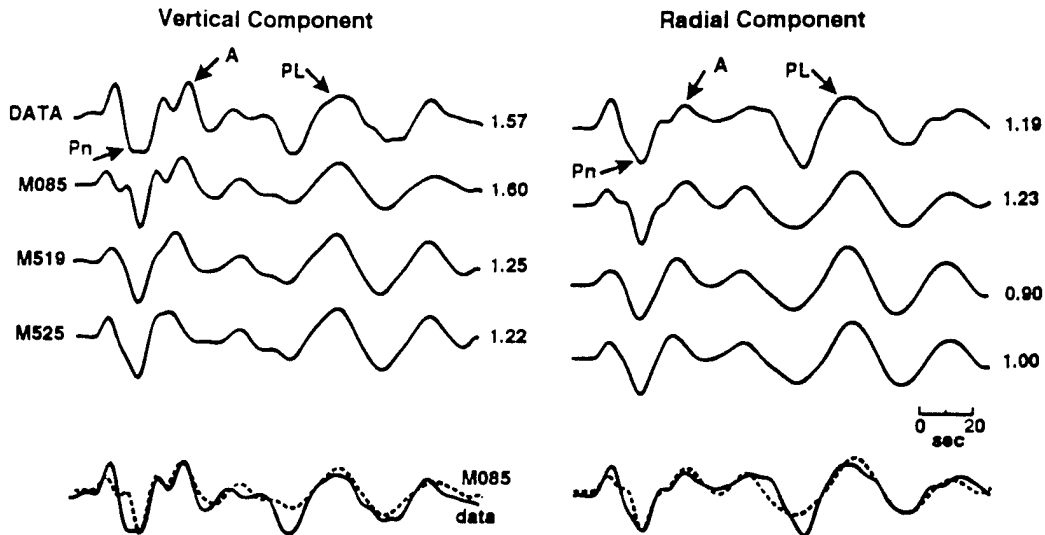## Event 1 BCAO

Vertical Component

Radial Component

Figure 3: Data and synthetic seismograms for Event 1 (Figure1) recorded at BCAO (BGCA) station. Earth models are shown in Figure 4. Same scheme as Figure 2.
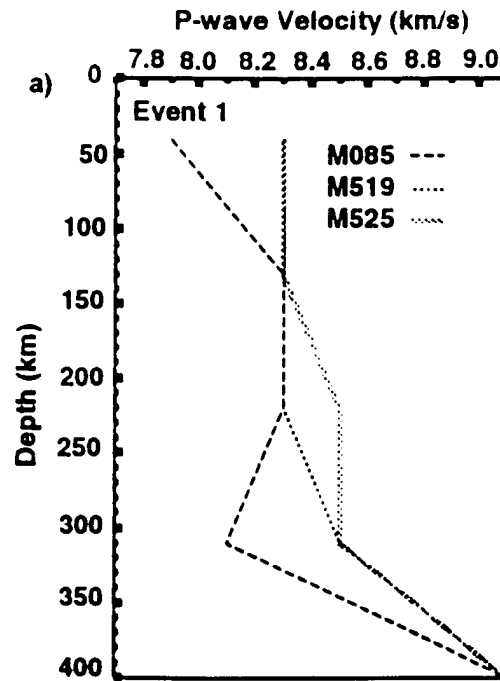
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Figure 4: P-wave velocity models obtained from a systematic grid search procedure that satisfy traveltime and amplitude constraints for the Pnl waveform data of Figure 3.

Upper Mantle Structure Beneath Southern Africa

20 Broadband seismic stations were installed within the country of Tanzania, East Africa, as part of an NSF funded project from May 1994 through June 1995 [*Nyblade et al.*, 1996a; *Owens et al.*, 1995]. Continuous, broadband, three-component seismic data were collected over the deployment primarily for the purpose of determining structure within the Tanzania craton and adjacent rift zones. This network recorded numerous teleseisms, among them being a large m_b 5.6 mine tremor which occurred at the President Brand Gold Mine in South Africa (Figure 1).

The data recorded by the network were remarkable in being high signal-to-noise and showing spectacularly simple P-wave triplications from the upper mantle discontinuities near 410km and 670km (Figure 5). Based on the location of the source and receivers, turning rays for this data set sample a region at the northern end of the Kalahari craton (Figure 1). Thus, we took advantage of the opportunity afforded by this data set to investigate the structure of the upper mantle in a region for which there is little information. Our previous Pnl modeling allowed us to infer general characteristics of the P-wave velocity and gradient within the upper 200 km, but this new data set offered us the means to probe more deeply under a major African craton for the first time.

The results of this study are part of a submitted paper by *Zhao et al.* (1997) and will only be summarized here. The data were analyzed using a combination of travel time inversion using the Weichert-Herglotz technique and waveform modelling via accurate wavenumber integration methods. Basically, trial traveltime curves were placed on record sections of the observed waveform data to place bounds on the location of cusps of the
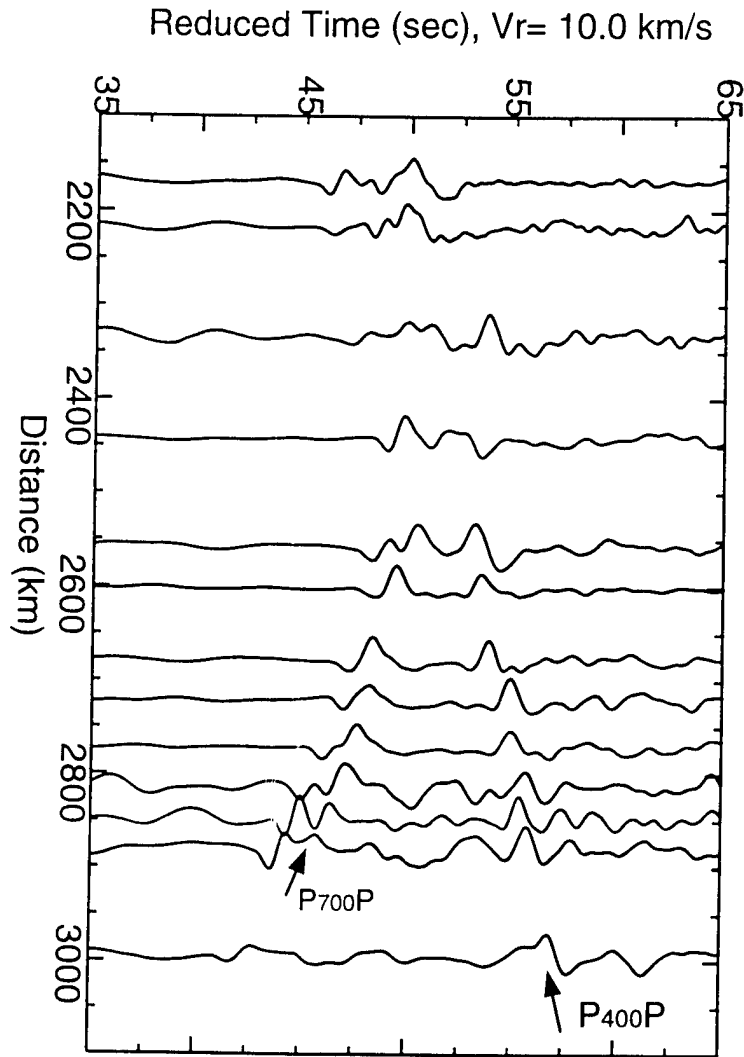
Figure 5: Vertical displacement seismograms recorded by the Tanzania network from the 10/30/94 South African mine tremor. P700P denotes the traveltime branch for the refraction under the 670 "discontinuity" and P400P denotes the back branch of the 400 km "discontinuity". Traveltime has been reduced using a reducing velocity of 10 km/s.

triplications. These traveltime curves were represented by simple polynomials which were then integrated using the Weichert-Herglotz technique to find the vertical velocity function. The resulting velocity model was then used to compute synthetic seismograms. These were used in the final step of checking the consistency of relative amplitudes of the observed triplications. The final model is shown in Figure 6 with a comparison of data, synthetics from the final model, and synthetics for other published upper mantle models shown in Figure 7.

There are several striking features of the inferred upper mantle structure (Figure 6). Compared to the IASP91 model, which represents a model fitting average P-wave traveltimes over the entire globe, our model has relatively high velocities between the crust and 400 km without a noticeable upper mantle low velocity zone (LVZ). The gradient in this zone is relatively small with the upper part set by results from *Clouser and Langston* (1990). The upper mantle "discontinuites" at 410 km and 670 km are seen to be smooth transition zones of higher gradient rather than true discontinuites. These features are required both by the unusually large distance that the traveltime branch for the 410 km "discontinuity" stretches out to and by the very subdued nature of triplications seen associated with the 670 km discontinuity.

A sensistivity study showed that the data could only allow the existence of a small LVZ above 200 km depth. However, *Clouser and Langston* (1990) show that such zones are not seen in southern Africa from the Pnl data. Figure 7 also shows synthetic seismograms for several other models of shield structures which were initially examined as starting models for modeling. In addition to the IASP91 model [*Kennett and Engdahl*, 1991] ,
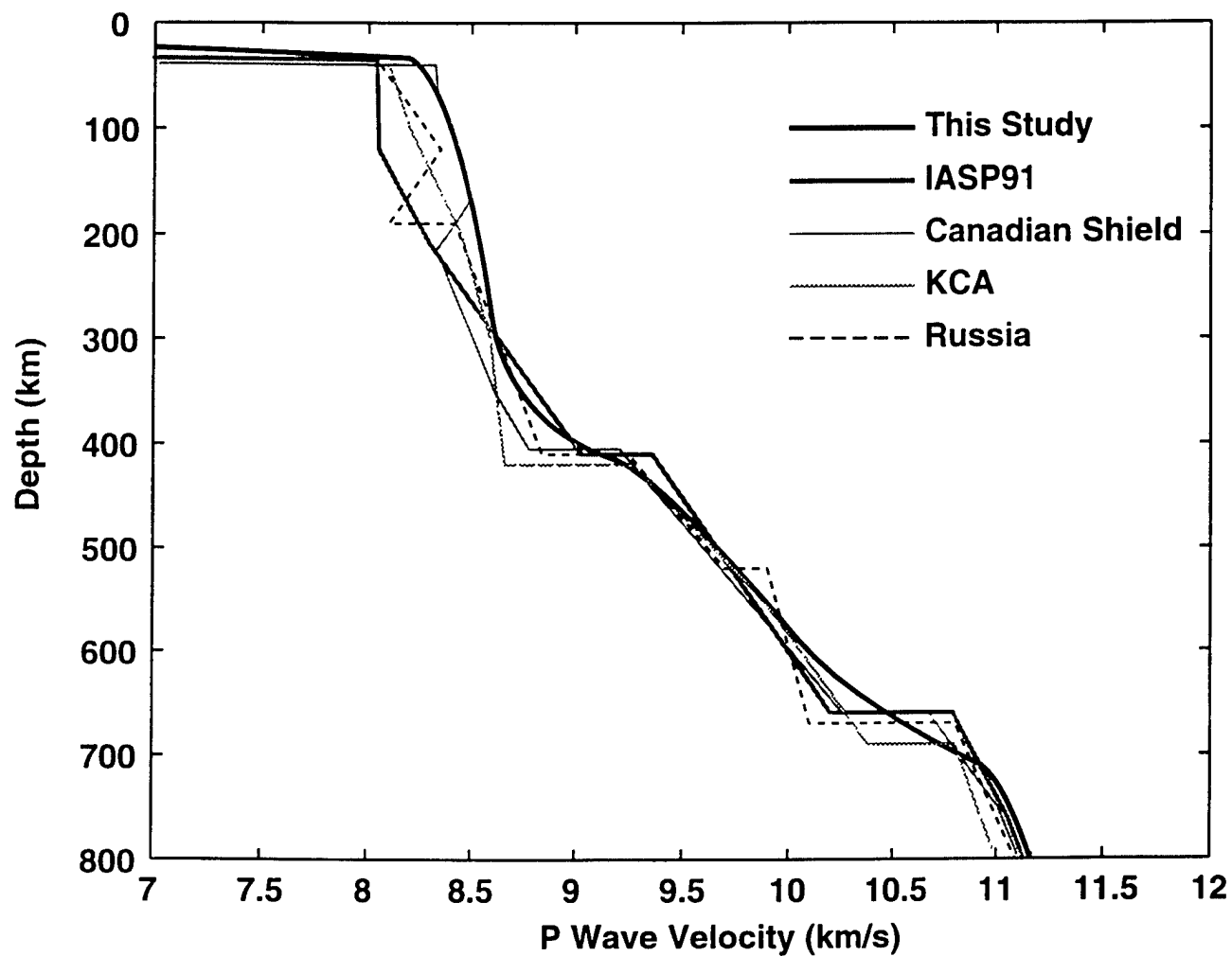
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Figure 6: Comparison of five upper mantle velocity models. The velocity function for this study is shown by the heavy line.
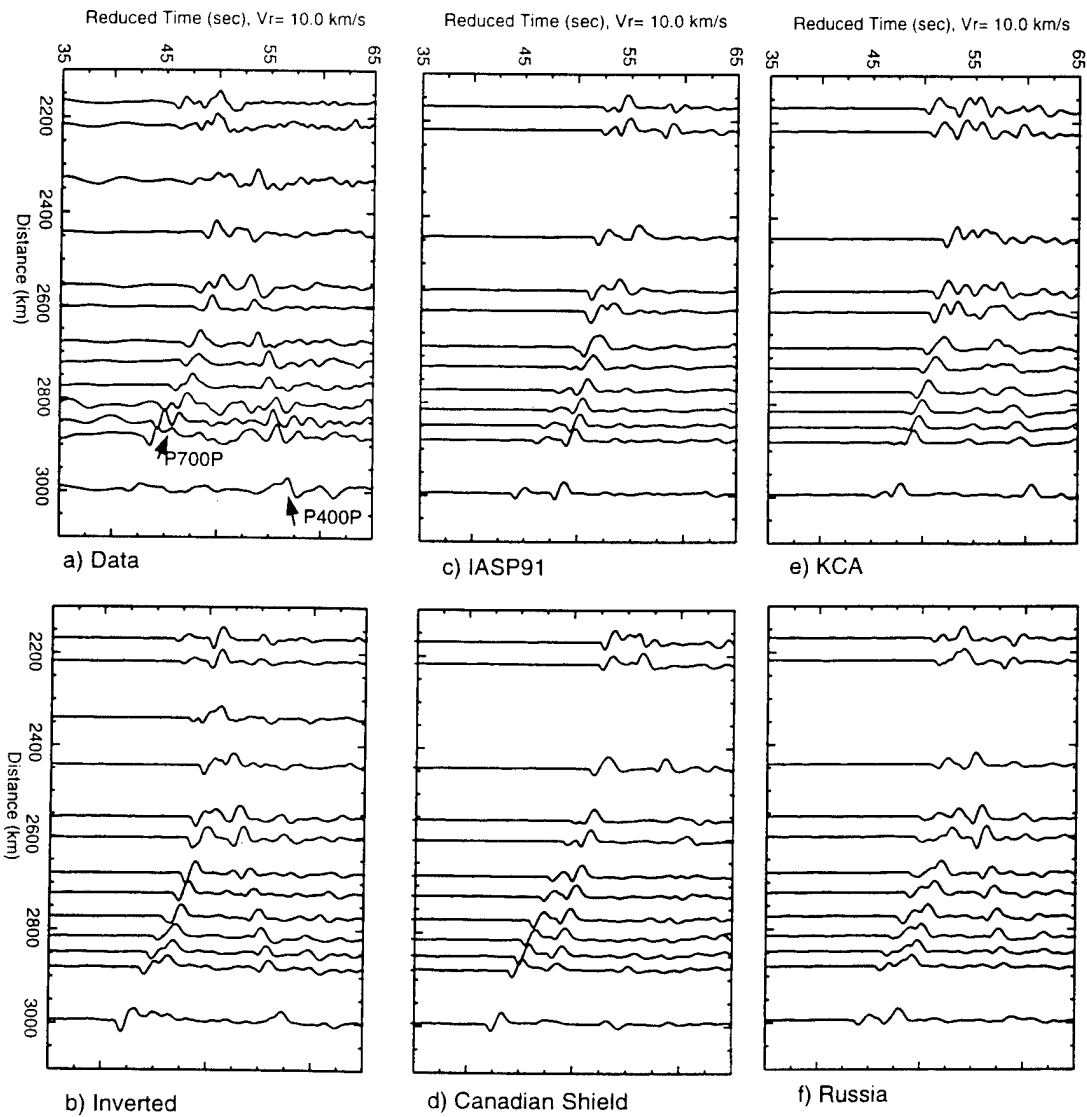
Figure 7: Comparison of data (upper left) and synthetic seismograms for the models shown in Figure 6. See text for details.

models for Fennoscandia (KCA) [*King and Calcagnile*, 1976], Russia [*Ryberg et al.*, 1996], and the Canadian shield [*LeFevre and Helmberger*, 1989] have been used to compare with the data. For these cases, the triplication for the 670 discontinuity is very large and distinct showing 2 or more large arrivals past distances of 2600 km. The data and inverted model show a relatively small triplication (P700P) over a fairly limited distance range. The KCA and Russia models show large P400P branches as does the data. This is due to the small velocity gradient just above the 410 km "discontinuity" and lack of a significant LVZ.

This comparison suggests that upper mantle structure in southern Africa is unique in the world and reflects true differences in structure between the major cratons. Overall high velocities also suggest that there are no significant thermal anomalies within the upper mantle under southern Africa which could be the source of the African Superswell. Again, the seismic data suggest that such compensation mechanisms must be sought in the lower mantle.

Regional Wave Propagation and Source Processes of South African Mine Tremors

A major ingredient in the study of upper mantle structure using data from the Tanzania network was determining the source processes of the m_b 5.6 South African event. In our preliminary look at the seismic data, we used source parameters published by *Fan and Wallace* (1995) to create synthetic seismograms. It quickly became apparent that these source parameters were inappropriate. Fan and Wallace suggested that the event occurred at 12 km depth which caused synthetics to be quite complicated due to the large separation in time of direct and surface reflected phases in the P waveforms.

Intrigued by this anomaly, we collected all available teleseismic and regional waveform data in an effort to determine the source depth and fault mechanism.

Fan and Wallace (1995) suggested that this event was a tectonic earthquake at mid-crustal depths. Figure 8 shows the location of recent seismicity in the area which is entirely associated with gold mining activities in the Witwatersrand Basin of South Africa. Indeed, McGarr (personal communication) indicated that this m_b 5.6 event was actually a mine tremor (rock burst) that occurred in the President Brand Mine causing damage and casualties. Thus, there was additional doubt that the published source parameters were appropriate for the event.

Figure 9 shows our preferred mechanism determined by modeling teleseismic P waveforms and local/regional P and S broadband displacements at BOSA station. Surprisingly, we obtained a much shallower depth of only ~1km for the event based on the extreme interference of P, pP and sP in the teleseismic P waves. Recently, *Bowers* (1997) published a thorough paper analyzing this event with teleseismic data and obtained a very similar result as ours.

We used these source parameters in modeling the Tanzania upper mantle waveforms. However, these mine tremors are interesting in themselves because they represent induced earthquakes which could come under scrutiny in monitoring compliance with the CTBT. It is important to not only determine accurate source parameters for these events but to also understand the wave propagation through the southern Africa crust and mantle. Basic monitoring requires knowledge of what seismic phases exist in a region as well as knowing how to use those phases to extract source parameters.
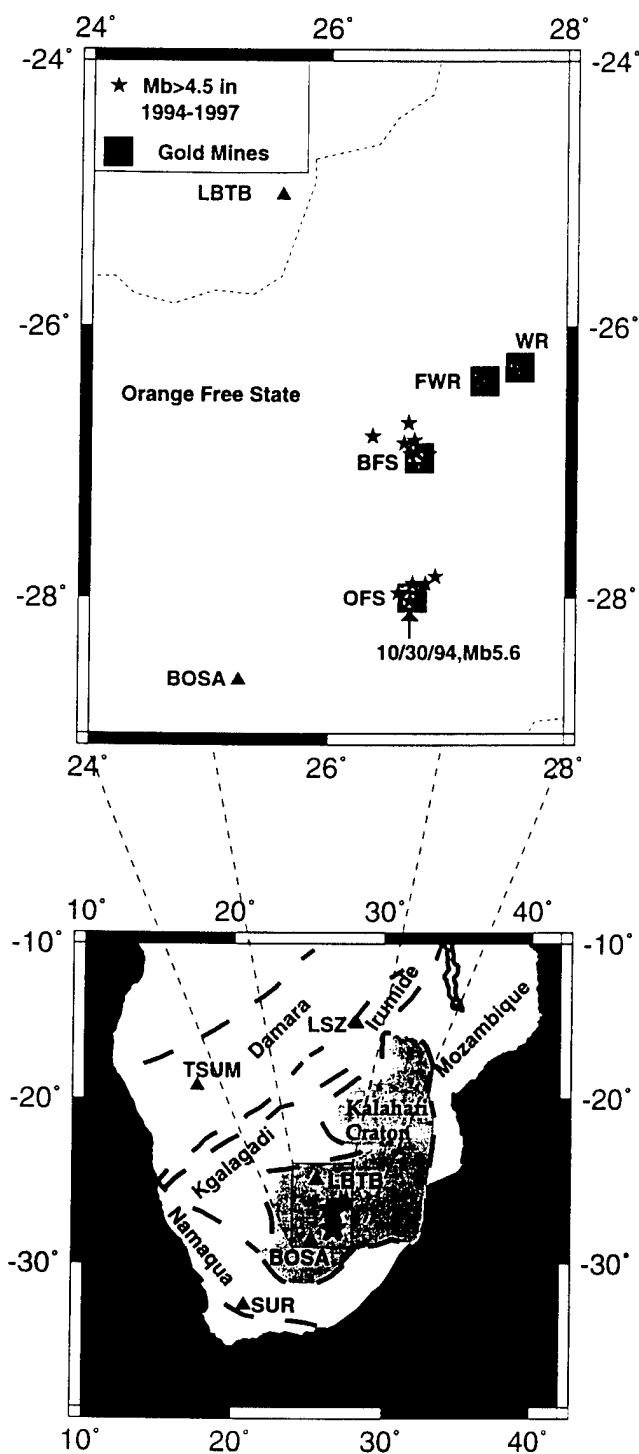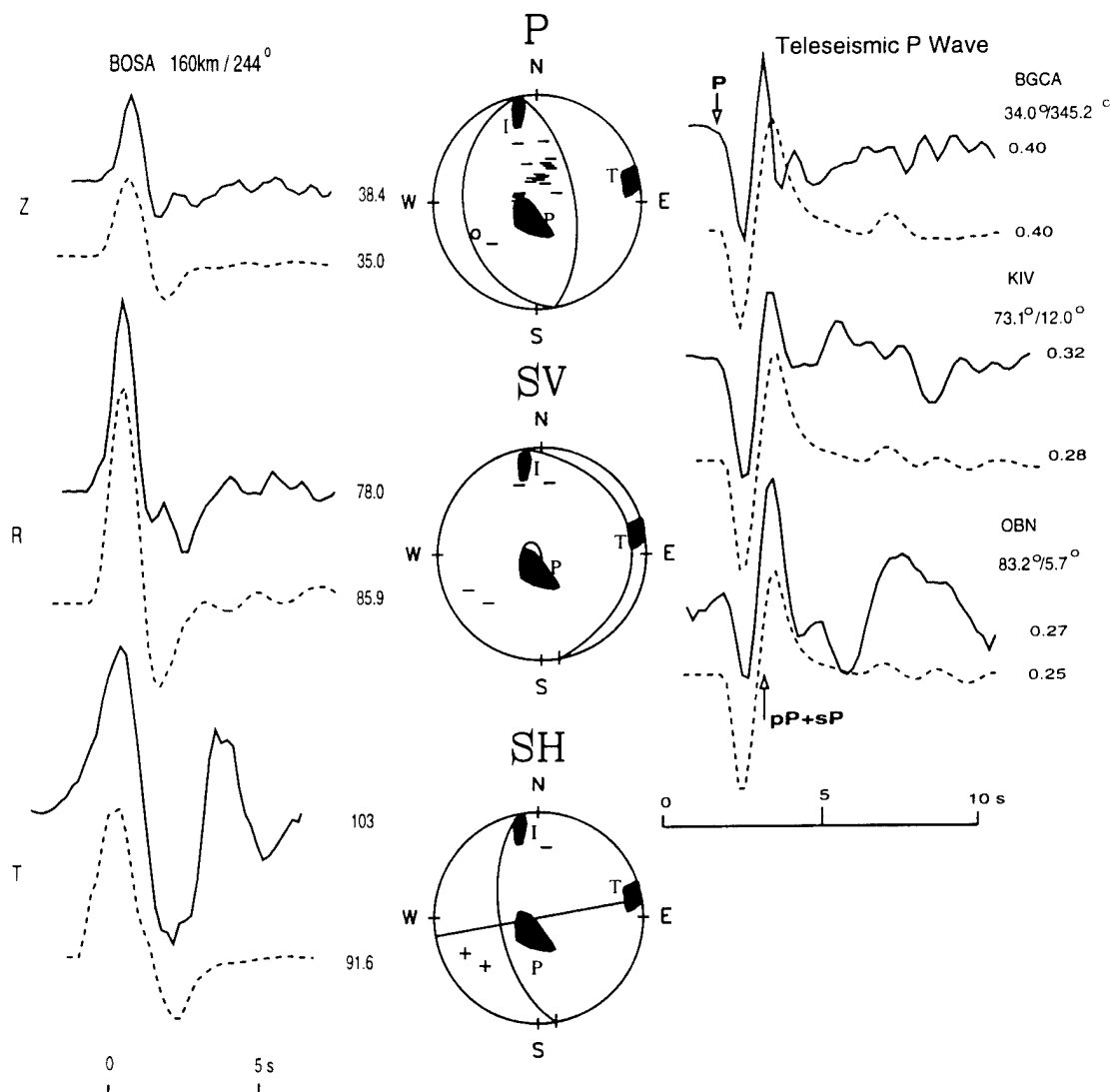
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Figure 8: Index map of southern Africa with detail on the seismicity of major gold mines within the Witwatersrand Basin.

BOSA 160km / 244°

P
N

SV
N

SH
N

Teleseismic P Wave

Z 38.4 / 35.0

W — E

BGCA
34.0°/345.2°
0.40
0.40

R 78.0 / 85.9

S

KIV
73.1°/12.0°
0.32
0.28

T 103 / 91.6

W — E

OBN
83.2°/5.7°
0.27
0.25

P

T

I

P

I

T

P

pP+sP

0   5   10 s

0   5 s

Mine Tremor
Source Depth: 1km
Nodal Plane I: strike, 170°-190°; dip, 30°-50°; rake,270°-300°
Nodal Plane II: strike, 320°-350°; dip, 40°-60°; rake, 255°-270°
Moment: 2.0*10^{23} dyne.cm
Non-double couple component: 45%

Figure 9: Data waveforms (solid lines) and synthetic waveforms (dashed lines) for the 10/30/94 mine tremor. Lower hemisphere projections of the P, SV and SH radiation patterns for the preferred mechanism is shown. These mechanisms were determined through an exhaustive grid search procedure on observed polarities and relative amplitudes. First motion polarities are shown on each and acceptable solutions are shown by the gray fields of Intermediate (I), Tension (T) and Compression (P) axes.

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As a follow-on to the research performed on this contract, we are in the midst of a study of five large mine tremors associated with these gold mines for the purpose of understanding the local and regional wave propagation. As an example, Figure 10 shows the waveform data for the m_b 5.6 event recorded at BOSA station at a range of 160 km. Synthetic seismograms have been computed for a series of source depths from 1 to 3 km. The vertical and radial components show the P wave arrival near 30 sec, an SV wave near 45 sec and the fundamental mode Rayleigh wave at 55 sec. The tangential component starts with crustal S and quickly grades into the fundamental mode Love wave. The crustal model for these synthetics is quite simple consisting of a thin (1km thick) low velocity layer over a linear gradient in velocity down to the Moho. Remarkably, much of the character of the seismograms is controlled by the thickness and velocity of the surface low velocity layer. The velocity of this layer was constrained by the Rayleigh group velocity dispersion determined directly from the data. Note the good fit to all phases for a source depth of 2 km. Clearly, this source must be shallow because of the large, well dispersed, high frequency Rayleigh waves.

As *Bowers* (1997) showed, this event displayed a very "explosion-like" m_b-M_s relation. Thus, it could be a candidate for a clandestine underground nuclear explosion, if it were not for the fact of having well recorded dilatational teleseismic P-waves. However, smaller events may be problematical if such auxilliary data are not available. Studies of this type in interesting areas are needed to fully appreciate sources and wave propagation characteristics for CTBT monitoring.
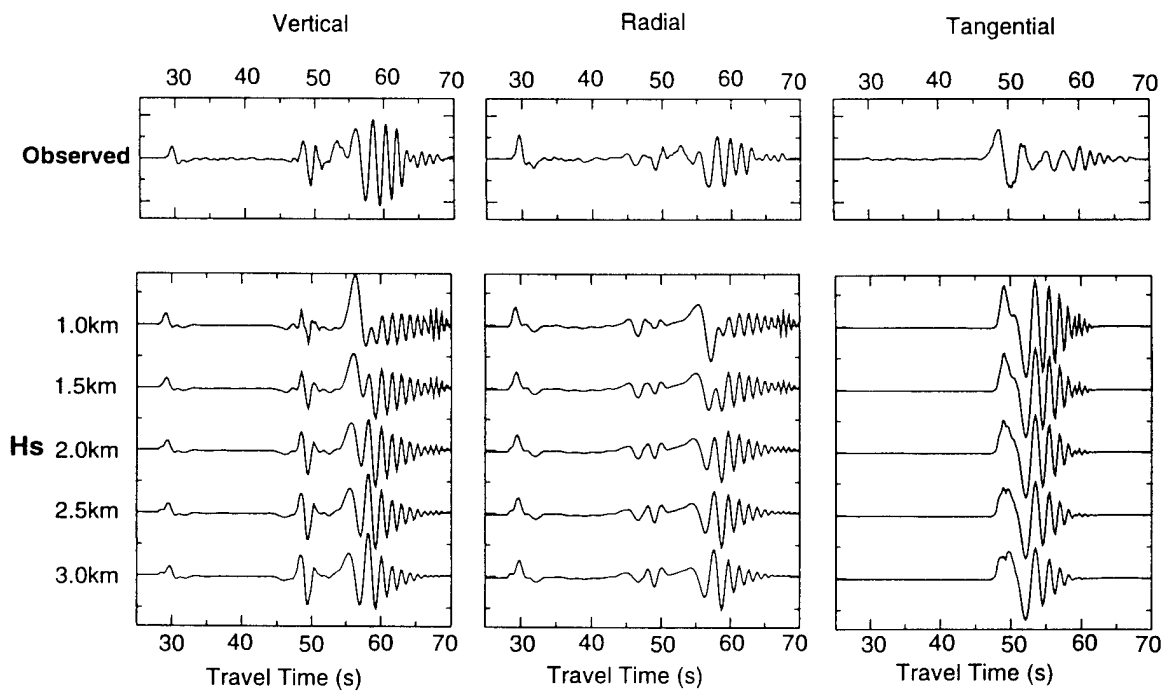
Figure 10: Observed (top) and synthetic (bottom) seismograms for the 10/30/94 mine tremor event recorded at BOSA. Distance is 160 km and a suite of synthetics has been computed for five different source depths.

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Geophys. Res.*, 101, 11,159-11,172 (1996).

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